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COMPARISON OF BALLISTIC PERFORMANCE OF A SPLIT HEAT OF ESR AND VAR 4340 STEEL

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METALS RESEARCH DIVISION

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ABSTRACT

A split argon-oxygen decarburized (AOD) heat of 4340 steel was used to compare the relative effectiveness of the VAR and ESR processes on ballistic performance. Forgings of VAR and ESR 4340 steel were rolled into plates with thicknesses of 0.64, 0.81, 0.96, 1.12, and 1.27 cm (0.25, 0.32, 0.38, 0.44, and 0.50 inch). Plates were heat treated to a tempered martensite microstructure by oil quenching and then tempering at 163, 171, 191, or 204°C (325, 340, 375, or 400°F).

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The protection limit (V_{50}) for a .50 caliber AP M2 threat was determined for ESR and VAR 4340 steel plates of several thickness-tempering temperature combinations. Results indicate that over the thickness range studied the protection limit for the ESR 4340 steel tempered at 171°C (340°F) is equal to or greater than that of the VAR 4340 steel. Also, within the tempering temperature range studied the 171°C (340°F) temper provides the greatest protection against the .50 caliber threat for 0.64-cm (0.25 inch) thick ESR 4340 steel plates. There is a greater tendency for VAR processed 0.64-cm (0.25 inch) thick plates tempered at 163 and 171°C (325 and 340°F) to crack when impacted by this threat than comparable ESR processed plates. Further, for both ESR and VAR 4340 steel plates tempered at 171°C (340°F) it is found that the penetration mechanism gradually changes from petalling to plugging as plate thickness increases. Keywords: Armor plate;

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INTRODUCTION

Enhancing aircraft and ground vehicle survivability is currently an area of great interest. There are a number of factors which relate to extended life. One factor of prime importance is the development and utilization of materials which increase the damage tolerance characteristics when used for either integral structural or component applications. Research and development efforts have addressed this from a materials aspect by considering composites, metal laminates, and metals in the monolithic form. Of major interest in this area to the Army Materials and Mechanics Research Center in recent years has been the development and characterization of specially processed steel for aircraft and ground vehicle application where ballistic tolerance is important.

The first major aircraft application of electroslag remelted (ESR) steel to improve survivability is in the Army's Advanced Attack Helicopter (AAH) Program. Electroslag remelted 4340 steel is used parasitically as driveshaft and hydraulic heat exchanger deflector armor. As integral armor, ESR steel is machined into ballistically survivable hydraulic actuators, rotor pitch links, bearing sleeves, crank assemblies, and scissors.[*,1] Recently, ESR 4350 steel backed with Kevlar was chosen for the Blackhawk utility helicopter crew seat.[2] The primary reason for selecting ESR steel is based upon its superior ballistic properties attributed primarily to improved shatter resistance accompanying a low sulfide inclusion content.[1-3] Lower estimated cost was also a significant factor; however, the present demand has not been sufficient enough to make electroslag remelting cost effective.

Electroslag remelting competes with vacuum arc remelting (VAR) and therefore its performance in terms of mechanical and ballistic properties should be compared. There has been a great deal of heat-to-heat variability in electroslag remelted ingots. For example, a recent study has shown that nine commercial heats of ESR 4340 steel purchased from three major producers did not meet required material property specifications at high hardness levels (HRC 55).[4] Short transverse mechanical properties revealed a severe loss of ductility due to grain boundary segregation of phosphorus and sulfur during solidification and austenitization.[4] A homogenization treatment was found to be essential at these extreme hardness levels.

The same embrittlement mechanism found in ESR steel was also detected in air-melted steel and vacuum induction melted 4340 steel.[3] It was impossible to make meaningful comparisons between the various remelting procedures due to the unusually high hardness level and lack of short transverse property data. Past comparisons have been made from heats of steel with dissimilar chemical compositions and having vastly different processing histories.

*McDERMOTT, J. M., and VEGA, E. *The Effects of Latest Military Criteria on the Structural Weight of the Hughes Advanced Helicopter.* Hughes Helicopters, Culver City, CA, Unpublished Work, 1977.

1. ROHTERT, R. E. *Ballistic Design Support Tests - A Tool for Helicopter Vulnerability Reduction.* Presented at the AHS 31st Annual National Forum, Preprint no. 984, May 1975.
2. PRIFTI, J. J., PAPETTI, D., and RICCI, W. *ESR Steel/Kevlar Armored Bucket Seat for Aircrew Protection.* Army Materials and Mechanics Research Center, Published in JTCG/AS Conference on Design of Armor Systems Proceedings, June 1983 (Confidential Report).
3. HICKEY, C. F., Jr., ANCTIL, A. A., and CHAIT, R. *The Ballistic Performance of the High Strength 4340 Steel Processed by Electroslag Remelting.* Proceedings on Fracture Toughness of Wrought and Cast Steels, E. Fortner ed., ASME MPC-13, 1980, p. 219-229.
4. OLSON, G. B., ANCTIL, A. A., DeSISTO, T. S., and KULA, E. B. *Anisotropic Embrittlement in High-Hardness ESR 4340 Steel Forgings.* Army Materials and Mechanics Research Center, AMMRC TR 82-1, January 1982.

This fact precipitated the need for a characterization study involving a split-heat comparison of electroslag and vacuum arc remelting processes. The phase of the split-heat comparison program which addressed the relative hydrogen embrittlement susceptibility and heat treatment distortion properties has been completed. The results indicated that the VAR material is less susceptible to hydrogen embrittlement and that essentially no difference exists in distortion propensity.[5] The mechanical property phase which addressed the effect of tempering temperature on hardness, tensile properties, V-notch Charpy energy, fracture toughness, and metallography, has also been completed. A summary of the results indicate the following: (1) nearly identical hardness and strength properties between the ESR and VAR processed 4340 steel; (2) higher impact energy values for VAR material tempered above 260°C (500°F); and (3) higher fracture toughness (K_{IQ}) for the VAR material for tempering temperatures ranging from 163 to 427°C (325 to 800°F).[6] It is believed that the lower toughness properties observed in the ESR material are associated with the presence of calcium aluminate inclusions and possibly, also with its higher gas content. This report will define and compare the ballistic performances as a function of tempering temperature and plate thickness. The protection limit values will be presented in a confidential report and will subsequently be published in an updated version of the "Ballistic Technology of Lightweight Armor."[7]

MATERIAL AND TESTING PROCEDURE

The material studied in this investigation was a split argon-oxygen decarburized (AOD) heat of 4340 steel which was remelted by the VAR and ESR process and forged into 12.7-cm (5 inch) square x 30.5-cm (12 inch) long forgings. These forgings were rolled into plates with thicknesses ranging from 0.65 to 1.3-cm (0.25 to 0.5 inch). The chemical composition as supplied by the producer for the AOD, VAR, and ESR conditions is shown in Table 1. A gas analysis was not obtained for the AOD condition, however the level of the other impurities in the AOD steel should be noted and their importance clearly understood. ESR processing removes sulfur where VAR processing does not. With the sulfur content at 0.001 w/o and the lower nitrogen, oxygen, and hydrogen this VAR heat of 4340 steel is considered to be of exceptionally high purity. This could not have been achieved without the low impurity level of the AOD heat. The decrease in manganese content during VAR processing was expected and is due to the high vapor pressure of this element.

Table 1. CHEMICAL COMPOSITIONS

Process	Weight Percent											
	C	Mn	Si	Ni	Cr	Mo	P	S	Cu	Al	N	O	Hppm
AOD	0.42	0.66	0.24	1.73	0.94	0.22	0.007	0.001	0.19	0.032	-	-	-
VAR	0.42	0.46	0.28	1.74	0.89	0.21	0.009	0.001	0.19	0.031	0.005	0.001	1.0
ESR	0.41	0.70	0.26	1.73	0.90	0.22	0.008	0.001	0.21	0.035	0.006	0.004	1.8

5. RAYMOND, L., and BENECKER, C. *Evaluation of the Relative Hydrogen Embrittlement Susceptibility of ESR 4340 and It's Heat Treat Distortion Properties.* Parker Hannifin Corporation, Contract DAAG46-81-C-0045, Final Report, AMMRC TR 82-49, September 1982.
6. HICKEY, C. F., Jr., and ANCTIL, A. A. *Split Heat Mechanical Property Comparison of ESR and VAR 4340 Steel.* Army Materials and Mechanics Research Center, AMMRC TR 83-27, May 1983.
7. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor - 1981 (U).* Army Materials and Mechanics Research Center, AMMRC TR 81-20, May 1981, (Confidential Report).

The plates were heat treated to a tempered martensite microstructure as follows: normalized at 927°C (1700°F) for 3 hours and air cooled, austenitized at 843°C (1550°F) for 2 hours then oil quenched, and tempered at 163, 171, 191, or 204°C (325, 340, 375, or 400°F) for 3 hours and air cooled. Respective Rockwell C hardness (HRC) values obtained from these tempers were 56.8, 55.1, 54.1, and 52.9.

The plate thickness-tempering temperature parameters selected for ballistic testing are as follows: (1) nominal 0.64-cm (0.25 inch) thick plate as a function of tempering temperature, (2) effect of nominal plate thickness [0.64, 0.81, 0.96, 1.12, and 1.27 cm (0.25, 0.32, 0.38, 0.44, and 0.50 inch)] tempered at 171°C (340°F), and (3) 1.27-cm (0.50 inch) thick plate tempered at 191°C (375°F).

The 30 cm x 30 cm x thickness (12 inch x 12 inch x thickness) plates were ballistically impacted at room temperature with .50 caliber AP M2 (armor piercing, hardened steel core) projectiles at 0° obliquity. Plates were secured by two clamps approximately 15 to 20 cm (6 to 8 inch) apart on each of two opposite sides. A protection limit (V_{50}), defined as the projectile velocity for which the probability of penetration is 50 percent was established for at least three plates of each condition. This limit was reported for each plate and determined by averaging at least four (and as many as six, depending on the plate) impact velocities comprising the two lowest velocities resulting in complete penetration and the two highest velocities resulting in partial penetration. A maximum spread of 38 m/s (125 ft/s) was allowed between the lowest and highest velocities employed in the determination of the protection limit. Complete penetration was defined when projectile or plate fragments pierced a 0.036 to 0.051-cm (0.014 to 0.020 inch) thick aluminum alloy sheet placed six inches behind and parallel to the tested plates.[8]

This report addresses a ballistic comparison of ESR and VAR 4340 steel, plus various related parameters such as projectile type damage and optimum plate protection thickness. Photographs of typical impacted plates are included in the comparison.

RESULTS AND DISCUSSION

Mechanical Properties and Microstructural Characterization

It is necessary to characterize the investigated materials in terms of specific mechanical properties since ballistic results are viewed as particular to these heats and not the generic 4340 steel. Tensile strength, 0.2% yield strength (Table 2), Charpy impact energy (Table 3), and fracture toughness (K_{IQ}) (Table 4) for the ESR and VAR 4340 steel tempered at 163, 171 and 204°C (325, 340, and 400°F) have been obtained previously and are reproduced here.[6] For a given temper the tensile and yield strengths of the two steels are similar. There is scatter in the Charpy impact energy data but there does not appear to be a significant difference between the ESR and VAR Charpy impact energy values. The VAR 4340 steel has a higher fracture toughness than the ESR 4340 steel for each of the tempering temperatures. It should be understood that there was a slight difference in the heat treating of the specimen blanks for the mechanical property phase[6] than for the impacted plates. Specimen blanks were normalized at 899°C (1650°F) for 1 hour and air cooled, austenitized at 843°C (1550°F) for 1 hour and oil quenched and tempered as above for 1 hour.

8. *Security Classification Guide for Armor Materials.* MSR no. 01813009, Army Materials and Mechanics Research Center, January 1980.

Table 2. EFFECT OF TEMPERING TEMPERATURE ON THE LONGITUDINAL TENSILE PROPERTIES OF VAR AND ESR 4340 STEEL[6]

Temper		VAR				ESR			
		0.2% YS		UTS		0.2% YS		UTS	
°C	°F	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
163	325	1590	231	2160	314	1610	233	2170	314
171	340	1610	234	2150	312	1620	235	2150	312
204	400	1620	235	2000	290	1610	233	1990	289

Table 3. EFFECT OF TEMPERING TEMPERATURE AND ORIENTATION ON THE CHARPY IMPACT ENERGY OF VAR AND ESR 4340 STEEL[6]

Temper		Longitudinal (LT)				Transverse (TL)			
		VAR		ESR		VAR		ESR	
°C	°F	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb
163	325	25.5	18.8	24.4	18.0	25.5	18.8	25.8	19.0
						21.7	16.0	18.4	13.6
						17.6	13.0	19.0	14.0
171	340	22.9	16.9	23.4	17.3	27.0	19.9	22.4	16.5
		24.4	18.0	24.3	17.9	21.4	15.8	21.4	15.8
						22.6	16.7		
204	400	27.0	19.9	25.8	19.0	20.6	15.2	24.7	18.2
		27.0	19.9			24.7	18.2	24.1	17.8
						21.4	15.8		

Table 4. EFFECT OF TEMPERING TEMPERATURE AND ORIENTATION ON THE FRACTURE TOUGHNESS (K_{IQ}) OF VAR AND ESR 4340 STEEL[6]

Temper		Longitudinal (LT)				Transverse (TL)			
		VAR		ESR		VAR		ESR	
°C	°F	MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa$\sqrt{m}$	ksi$\sqrt{in.}$
163	325	55.0	50.1	50.2	45.7	56.3	51.2	47.3	43.0
		56.8	51.7	49.0	44.6	52.2	47.5	49.1	44.7
171	340	56.9	51.8	52.6	47.9	57.8	52.6	50.9	46.3
		65.4	59.5	51.5	46.9	58.5	53.2	53.3	48.5
204	400	73.2	66.6	64.1	58.3	73.6	67.0	63.2	57.5
		65.9	60.0	63.3	57.6	69.9	63.6	62.1	56.5

The tempered [163°C (325°F)] martensite microstructure of the ESR 4340 steel plates is presented in Figure 1, and is also representative of the microstructure of the VAR 4340 steel plates. A characterization of the microstructure as a function of tempering temperature for these steels has been performed;[6] and ASTM grain size of 8 to 9 was found for all specimens.

Ballistic Properties

Protection limit (V_{50}) as a function of plate thickness, 0.64 to 1.21 cm (0.25 to 0.48 inch) is graphically illustrated in Figure 2 for the ESR and VAR processed steels tempered at 171°C (340°F). Only a slight difference is noted in the resistance to ballistic penetration between the ESR and VAR 4340 steels. Due to this slight difference only one curve could be drawn.

The scatter in the results decreases as plate thickness increases. A comparison of the V_{50}'s at a thickness of 0.64 cm (0.25 inch) to those at 0.82 cm (0.32 inch) is a good example. Also, at a thickness of 0.64 cm (0.25 inch) the scatter in V_{50} is much greater for the VAR 4340 steel than for the ESR 4340 steel. As expected from Reference 7, the slope of the curve decreases as thickness increases for this thickness range.

A comparison of the protection limits between the ESR and VAR 4340 steels as a function of tempering temperatures ranging between 163 and 204°C (325 and 400°F) is made in Figure 3. The ESR processed steel shows a maximum V_{50} for a 171°C (340°F) temper, while for tempering temperatures higher or lower than this, the protection limit decreases. A well defined relationship between protection limit and tempering temperature is not discernable for the VAR 4340 steel because the 171°C (340°F) temper produces two high and two extremely low V_{50}'s. However, the 204°C (400°F) temper produces lower V_{50}'s in the VAR and ESR processed steels than the 163°C (325°F) temper. This trend is also shown in Reference 3 for ESR 4340 steel. There is more of a decrease in V_{50} between the 191 and 204°C (375 and 400°F) tempers for the ESR 4340 steel than the VAR 4340 steel. Figure 4 compares the protection limits between the ESR and VAR 4340 steel for the 171°C (340°F) temper, represented by the solid line, and the 191°C (375°F) temper, given by the dashed line, as a function of thickness. The 191°C (375°F) temper gives a slightly lower V_{50} than the 171°C (340°F) temper, for both ESR and VAR processed steels for the two investigated plate thicknesses. Given the results in Figures 2, 3, and 4, it is observed that over the range of investigated test parameters the protection limit of the ESR 4340 steel is equal to and in some case superior to that of the VAR 4340 steel.

Photographs of nominal 0.64-cm (0.25 inch) thick ESR and VAR 4340 steel plates tempered between 163 and 204°C (325 and 400°F) and ballistic tested are presented in Figures 5 and 6. (Ascending numbers on plates correspond to decreasing projectile velocities.) As can be observed, there is cracking and attendant target removal (holes larger than the projectile size) for VAR and ESR processed plates tempered at 163 and 171°C (325 and 340°F). For those plates tempered at 191 and 204°C (375 and 400°F), however, the holes are circular and commensurate with the projectile diameter. In addition, the 0.64-cm (0.25 inch) thick VAR plates tempered at the two lower temperatures exhibited more cracking than comparable ESR steel plates. In fact, shattering is observed in two of the four 0.64-cm (0.25 inch) thick VAR 4340 steel plates tempered at 163°C (325°F). These are indications that the ESR 0.64-cm (0.25 inch) thick processed material would possess greater multi-hit capability for these lower tempering temperatures.

The principal penetration mechanism for the 0.64-cm (0.25 inch) thick ESR and VAR 4340 steel plates tempered at 171°C (340°F) is petalling. Bulging due to partial penetration and cracking due to complete penetration (break off of petals) are noticed at the rear surface (projectile exit) of these plates (Figures 5c, 5d, 6c, 6d). Plugging is the only operable penetration mechanism for the 1.21-cm (0.48 inch) thick ESR and VAR steel plates tempered at 171°C (340°F). These plates (Figures 7g, 7h, 8g, 8h) do not show the cracking and bulging characteristic of the thinner plates. The ESR and VAR plates of the same temper having a thickness between 0.64 and 1.21 cm (0.25 and 0.48 inch) have damage indicative of a transition from petalling to plugging as plate thickness increases (Figures 5c, 5d, 6c, 6d, 7a-7f, 8a-8f). As plate thickness increases from 0.64 to 1.21 cm (0.25 to 0.48 inch), the amount and degree of both cracking and bulge size decrease.

Photographs of approximately 1.1-cm (0.43 inch) thick ESR and VAR processed plates tempered at 191°C (375°F) are presented in Figures 9 and 10. With regard to plate damage there is no difference between the penetrations in these ESR and VAR 4340 steel plates tempered at 191°C (375°F) and plates of similar thickness tempered at 171°C (340°F) as shown in Figures 7g, 7h, 8g, and 8h.

Factors Influencing Ballistic Behavior

It is seen that the protection limits (V_{50}) are similar for VAR and ESR 4340 steels tempered at 171°C (340°F) within the plate thickness range of 0.64 to 1.21 cm (0.25 to 0.48 inch) (Figure 2). The processing history of the materials aid in confirming this result. The AOD heat from which both ESR and VAR processed materials originated was of very high purity (Table 1); note the low sulfur and phosphorus contents. As a result it was expected that these commercially processed VAR and ESR heats would also be of high purity.

The value which has resulted in the producer starting with a high purity AOD primary heat is shown in two points. First, because of the low sulfur level (0.001 w/o) any differences between these two steels will not be a result of sulfur content. Second, there are some questions to the extent that the ESR and VAR processes provide minimal chemical macro- and micro-segregation and freedom from porosity.[9] Thus, these variables have been isolated to a greater extent with the use of this low impurity AOD primary heat. In Figure 2, it is realized that if differences (e.g., segregation) do exist betwen the ESR and VAR processed steels examined here, they are not manifest in the protection velocity. On the other hand, Figures 5a, 5b, 6a, 6b, 7a-7d, 8a-8d and observations of all 0.64-cm (0.25 inch) thick ESR and VAR 4340 steel plates tempered at 163°C (325°F) and ballistic tested revealed a slightly greater tendency toward cracking in the VAR processed steel than in the ESR processed steel. This may be a result of these process related variables. It should be realized that these comments pertain to the ESR and VAR processes as they apply to a clean AOD heat. It is expected that differences between the processes would be amplified if a "dirty" AOD heat were to be used.

The result from the comparison in Figure 2 is significant for several other reasons. First. the VAR processed steel had higher static fracture toughness (K_{IQ}) at the 171°C (340°F) temper than the ESR processed steel (Table 4). The ballistic results can not be rationalized in terms of a correlation between static fracture toughness (K_{IQ}) and protection limit for the specific conditions in which testing was performed. However, it is acknowledged that dynamic fracture toughness may

9. *ESR Steels for Defence - State of the Art*. MRL-R-879, Materials Research Labs, Melbourne, Australia, 1982.

provide a correlation. Second, the VAR 4340 steel had a much lower manganese content than the ESR 4340 steel (Table 1). However, the ESR and VAR have equivalent protection limits over the 0.81 to 1.21-cm (0.32 to 0.48 inch) thickness range.

For these steels, it is known that hardness decreases as tempering temperature increases.[6] It is expected that the V_{50} increase to a maximum as tempering temperature decreases before it drops as a result of brittleness.[3] This trend is observed for the ESR 4340 steel which obtains a maximum V_{50} from the 171°C (340°F) temper and not the 163°C (325°F) temper (Figure 3). If it were not for the two extremely low V_{50}'s for the VAR 4340 steel tempered at 171°C (340°F) this temper might also give a maximum V_{50} for the VAR 4340 steel.

Nominal 1.27-cm (0.50 inch) thick ESR and VAR 4340 steel plates were also tempered at 191°C (375°F) and ballistic tested. Figure 4 shows V_{50} results for both thicknesses of plates tempered at 191°C (375°F) compared to results from plates tempered at 171°C (340°F). Both ESR and VAR processed steels exhibit a slight drop in V_{50} with increasing tempering temperature as expected and outlined previously.

Overall, it is seen that the protection limits over the entire range of thicknesses and tempering temperatures explored were at least as high for the ESR 4340 steel as for the VAR 4340 steel under equivalent conditions (Figures 2, 3, and 4). This similarity in ballistic protection is also manifest in the similarity of ballistic penetration appearance between the ESR and VAR 4340 steels, given equivalent conditions (Figures 5 versus 6, 7 versus 8, and 9 versus 10), except for shattering in 0.64-cm (0.25 inch) thick VAR processed steel plates, as already mentioned.

Figure 11, a graph of protection limit normalized with respect to areal density as a function of thickness, is a result of an effort to find the optimum ballistic protection in terms of plate thickness for the ESR and VAR 4340 steels within the investigated thickness range. After normalizing data in Figure 2, it is evident that there is an optimum normalized protection limit (Figure 11). The resolution of the data will only allow a generalization to the affect that both the ESR and VAR processed steels exhibit optimum ballistic protection with respect to thickness for a plate thickness between 0.64 and 0.83 cm (0.25 to 0.32 inch).

It is tempting to try to explain the shape of the curve in Figure 11 as a result of penetration mechanism changing with plate thickness. In fact, Figures 12a through 12f reveal typical penetrations for 0.64, 0.91, and 1.14-cm (0.25, 0.36 and 0.45 inch) thick ESR 4340 steel plates tempered at 171°C (340°F). [The following generalizations apply equally well to both processed steels with the exception of the VAR plates which exhibited shattering at the 163°C (325°F) temper.] In the thinner plate (Figures 12a and 12b) there is much tearing and a large oblong hole is produced. This is indicative of a petalling failure mechanism. Figures 12c and 12d [0.92-cm (0.36 inch) thick plate] reveal a "countersunk" hole on the front, slight tearing, and a small hole at the back. It is felt that plates of this thickness lie in a transition region which combines both petalling and plugging as the penetration mechanism. The thickest plate (Figures 12e and 12f) has a large entry and exit hole with plugging as the penetration mechanism. There is also no external evidence of cracking as in the two thinner plates. These are admittedly generalizations, however, Figures 12a through 12f, and on a larger scale, Figures 6c, 6d, 8c, 8d, 8g, and 8h reveal that there is a difference as to how complete penetration occurs, or how the plates resist penetration in plates of different thickness.

Indeed, Reference 10 cites a change in penetration appearance as plate thickness increases for a different projectile-steel combination. Further, it has been posited that the stress state in impacted plates is a function of the ratio of the projectile diameter to the plate thickness.* A change in stress state is coincident with a change in penetration mechanism. The physical and practical significance of Figure 11 will be addressed in future work (e.g., in exploring steel laminates for thicknesses greater than the optimum thickness range defined).

As illustrated in Figures 2 and 11, the scatter in V_{50} is much greater in the 0.64 to 0.80-cm (0.25 to 0.31 inch) thickness range than in the 0.80 to 1.27-cm (0.31 to 0.50 inch) thickness range. This wide scatter is attributed to the extreme sensitivity of V_{50} to thickness in the lower thickness range. Therefore, it is expected that the inclusions found in these materials[6] would be more deleterious to V_{50} in the lower thickness range.

It is important to note that differences between the ESR and VAR 4340 steel, either in mechanical property or protection limit data, have not been a result of differences in hardenability. First, for the plate thickneses and heat treatments investigated, equivalent hardness were achieved for both ESR and VAR 4340 steel. Second, according to U.S. Steel's hardenability slide rule (1970) and chemistries given in Table 1,† the ideal diameter for the VAR processed steel is 12.2 cm (4.8 inch) and for the ESR processed steel it is 16.0 cm (6.3 inch). The oil bath in which the steels were quenched had moderate circulation so its H-value is approximately 0.4.[11] This gives a critical diameter of 7.6 cm (3.0 inch) to the VAR 4340 steel and 10.7 cm (4.2 inch) to the ESR 4340 steel. In terms of cooling rate, a 7.6-cm (3.0 inch) bar diameter corresponds to a 5.6-cm (2.2 inch) plate thickness, and a 10.7-cm (4.2 inch) bar diameter corresponds to a 7.9-cm (3.1 inch) plate thickness.† So, there is no unhardened portion in the plates used here. Previous results have confirmed this observation.[6] Also, the plates are thin enough so that no through-thickness hardness variation occurred.[11]

CONCLUSIONS

1. The ESR and VAR 4340 steels obtained from a high purity AOD split heat and tempered at 171°C (340°F) exhibit similar protection limits and impact damage morphology at a given plate thickness for a .50 caliber AP M2 threat within the plate thickness range of 0.64 to 1.21 cm (0.25 to 0.48 inch). However, the 0.64-cm (0.25 inch) thick ESR 4340 steel plates have greater multi-hit capability (lesser cracking) than comparable VAR 4340 steel plates.

2. The rate of increase in protection limit for both ESR and VAR 4340 steels tempered at 171°C (340°F) decreases as plate thickness increases.

3. The 0.64-cm (0.25 inch) thick ESR 4340 steel has a higher protection limit when tempered at 171°C (340°F) than when tempered at 163, 191, or 204°C (325, 375, or 400°F).

*ROGERS, H. C. *Adiabatic Shearing: A Review.* Drexel University Report Prepared for the U.S. Army Research Office, 1974.
†United States Steel Hardenability Slide Rule, United States Steel, 1970.

10. CORRAN, R. S. J., SHADBOT, P. J., and RUIZ, C. *Impact Loading of Plates - An Experimental Investigation.* Int. J. Impact Eng., v. 1, no. 1, 1983, p. 3-22.
11. KRAUSS, G. *Principles of Heat Treatment of Steel.* American Society for Metals, Ohio, 1980.

4. There is more cracking in the 0.64-cm (0.25 inch) thick ESR and VAR 4340 steel plates tempered at 163 and 171°C (325 and 340°F) than plates tempered at 191 and 204°C (375 and 400°F). This is associated with the higher hardness levels obtained with the lower tempers.

5. The VAR 4340 steel tempered at 171°C (340°F) has significantly higher fracture toughness (K_{IQ}) than the comparable ESR 4340 steel. However, for a given thickness the former does not have a higher protection limit, which indicates that there is no correlation between static fracture toughness (K_{IQ}) and protection limit.

6. The VAR 4340 steel has a lower manganese content (0.46 w/o) than the ESR 4340 steel (0.70 w/o). However, for the 163°C (340°F) temper, the ESR and VAR have equivalent protection limits over the 0.81 to 1.21-cm (0.32 to 0.48 inch) thickness range.

7. Both 0.64 and 1.21-cm (0.25 and 0.48 inch) thick ESR and VAR 4340 steel plates have lower protection limits when tempered at 191°C (375°F) than when tempered at 171°C (340°F) because of the lower hardness obtained from the higher temper.

8. For the investigated thicknesses there is a maximum in ballistic protection with respect to thickness (i.e., protection limit normalized with respect to areal density) against the .50 caliber AP M2 threat for both the ESR and VAR 4340 steels tempered at 171°C (340°F) at a plate thickness between 0.64 and 0.83 cm (0.25 and 0.32 inch). It is suggested that this is associated with the observed change in penetration mechanism from petalling to plugging as plate thickness increases.

9. The impact damage morphology of the ESR and VAR 4340 steels tempered at 171°C (340°F) changes as plate thickness increases for projectile (.50 caliber AP M2) velocities near V_{50} [±19 m/s (62 ft/s)].

10. The excessive scatter in protection limit data for thin (less than 0.80-cm (0.31 inch) thick) ESR and VAR 4340 steel plates may be due to the observed rapid change in protection limit with small change in thickness at this thickness range.

SUMMARY

Over the range of investigated parameters the protection limit for the ESR 4340 exhibits equal or superior ballistic performance to that of comparable VAR 4340 steel in terms of protection limit (V_{50}) and multihit capability.

ACKNOWLEDGMENTS

The authors are grateful to Dr. E. B. Kula and Mr. J. F. Mescall for their helpful discussions.

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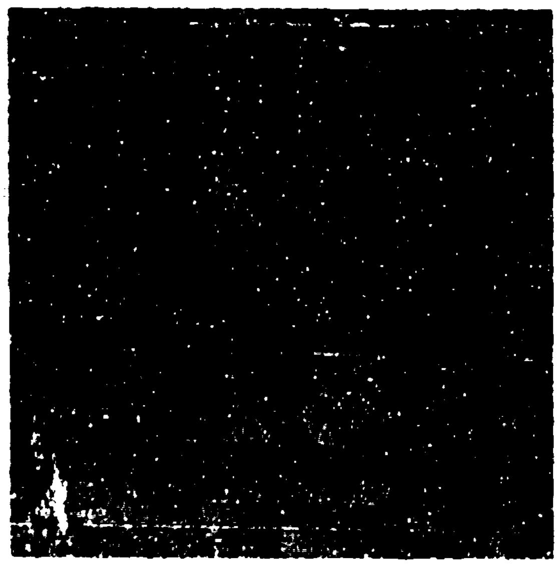
Etchant: 5% nital



Etchant: picral with sodium tridecylbenzene sulfonate, ASTM G. S. No. 9

Figure 1. Tempered martensite microstructure for ESR 4340 steel tempered at 163°C (325°F) for three hours (longitudinal). Mag. 500X

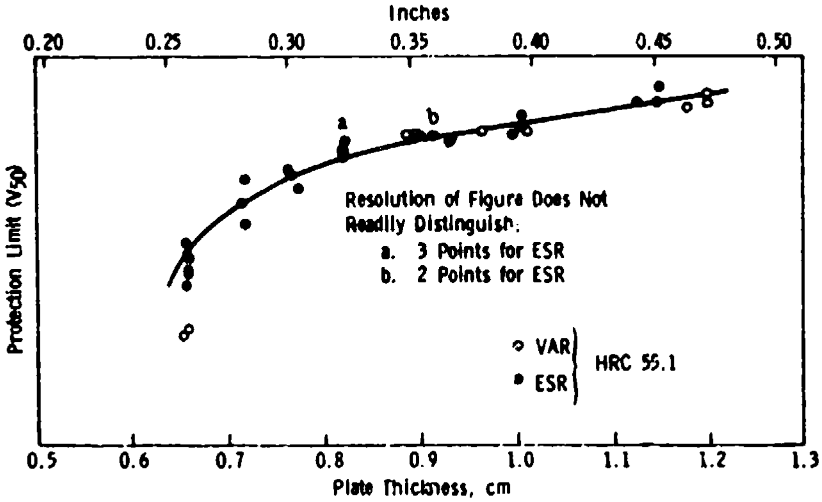


Figure 2. Protection limit (V_{50}) for .50 caliber AP M2 projectile as a function of thickness for ESR and VAR 4340 steel plates tempered at 171°C (340°F).

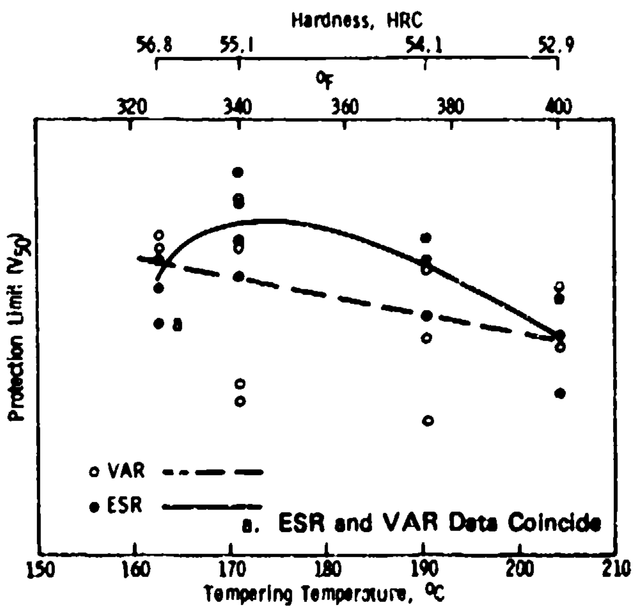


Figure 3. Protection limit (V_{50}) for .50 caliber AP M2 projectile as a function of tempering temperature for 0.64-cm (0.25 inch) thick ESR and VAR 4340 steel plates.

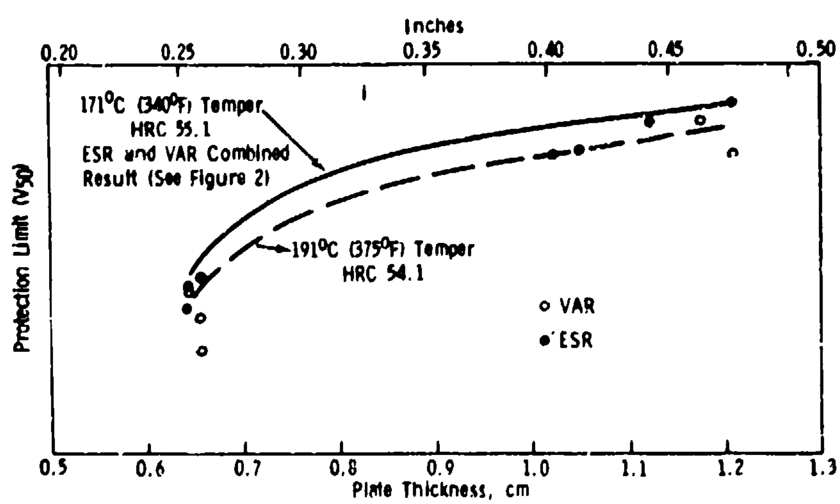
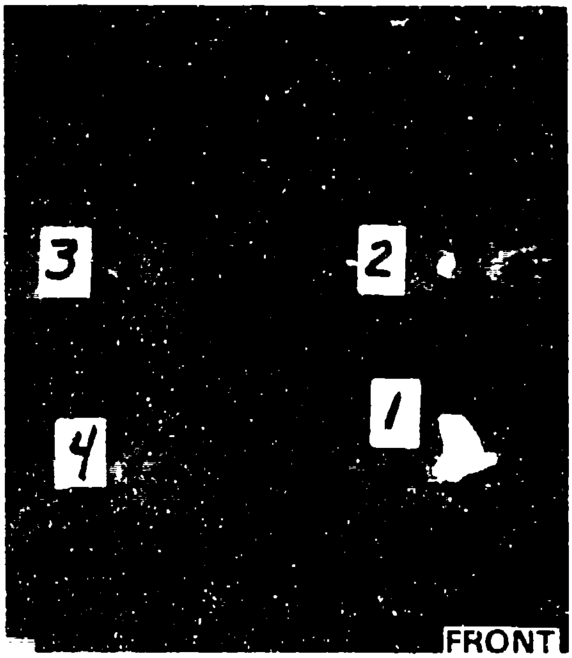
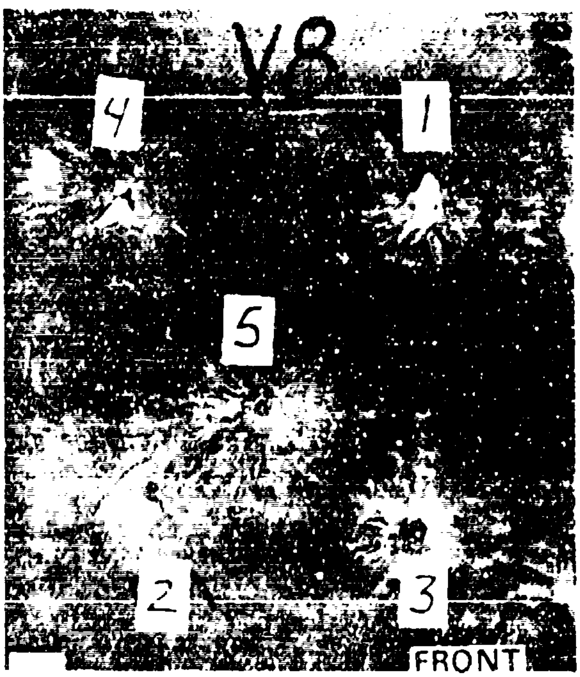


Figure 4. Protection limit (V_{50}) for .50 caliber AP M2 projectile as a function of thickness for ESR and VAR 4340 steel plates tempered at 171 and 191°C (340 and 375°F).

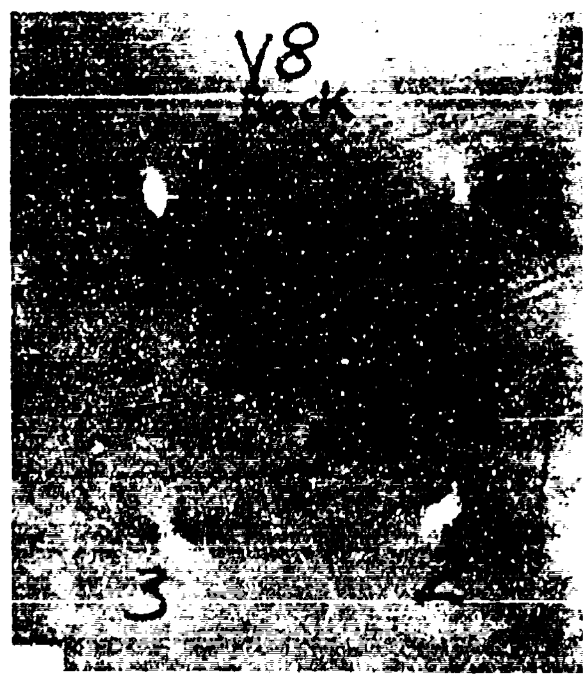


a. 163°C (325°F)

b. 163°C (325°F)

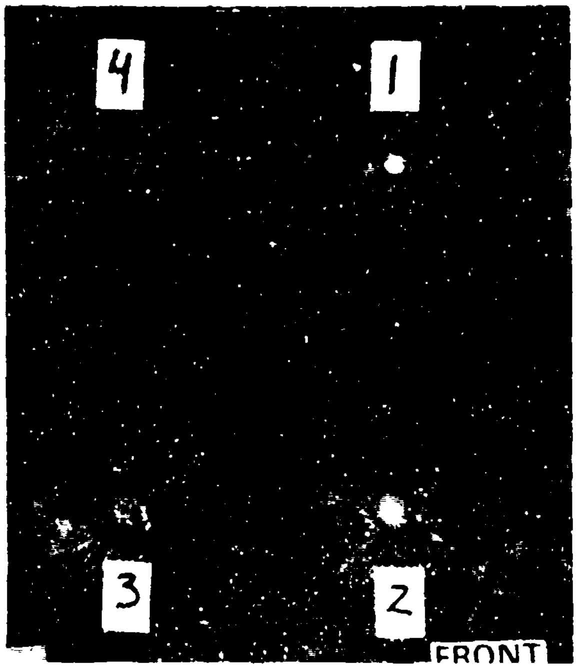


c. 171°C (340°F)



d. 171°C (340°F)

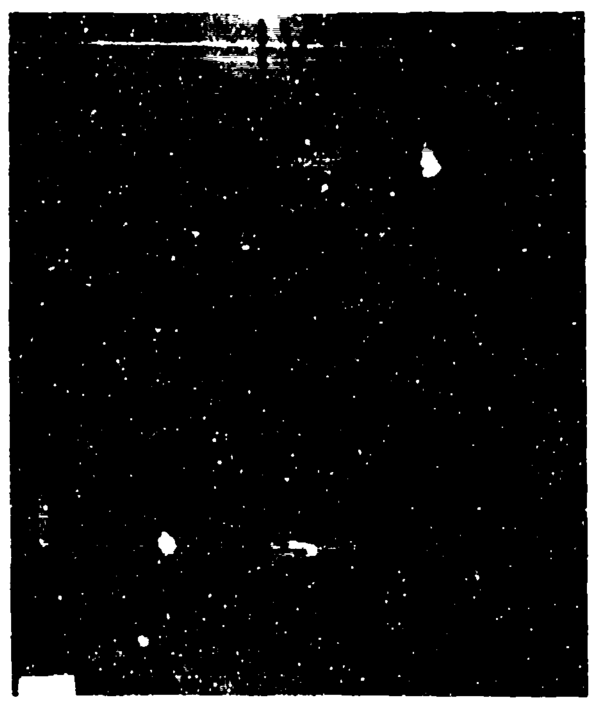
Figure 5. Ballistic tested VAR 4340 steel plates with a 0.635 cm (0.250 inch) nominal thickness as a function of tempering temperature. (75% reduction)



e. 191°C (375°F)

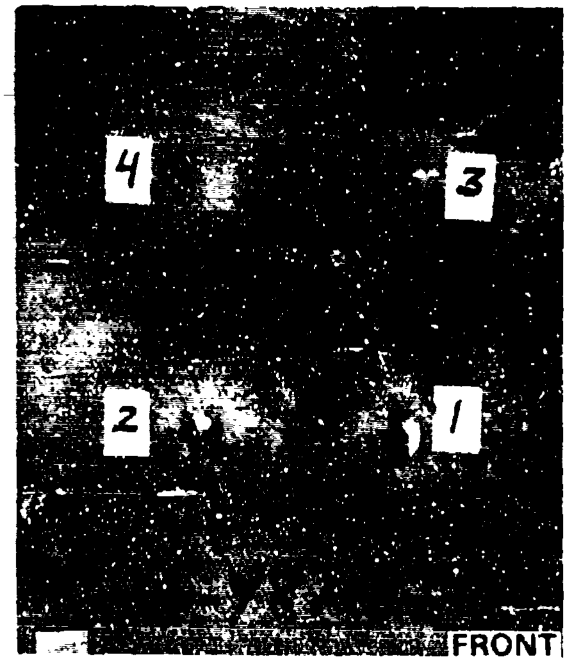
f. 191°C (375°F)

g. 204°C (400°F)



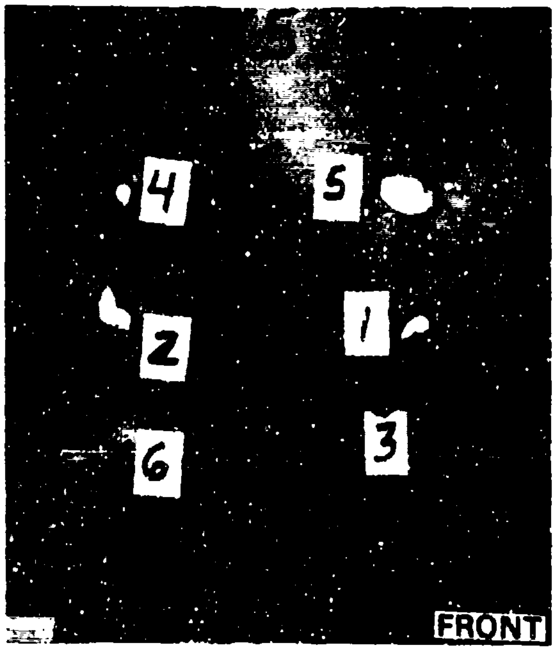
h. 204°C (400°F)

Figure 5. Ballistic tested VAR 4340 steel plates with a 0.635 cm (0.250 inch) nominal thickness as a function of tempering temperature. (75% reduction)

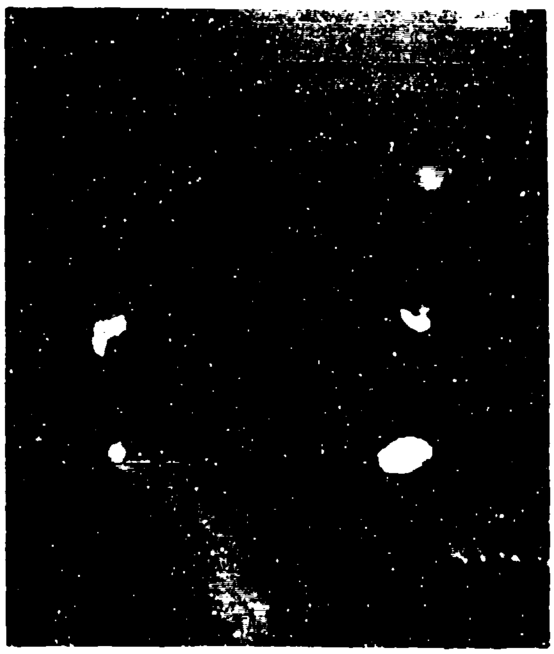


a. 163°C (325°F)

b. 163°C [illegible]°F)

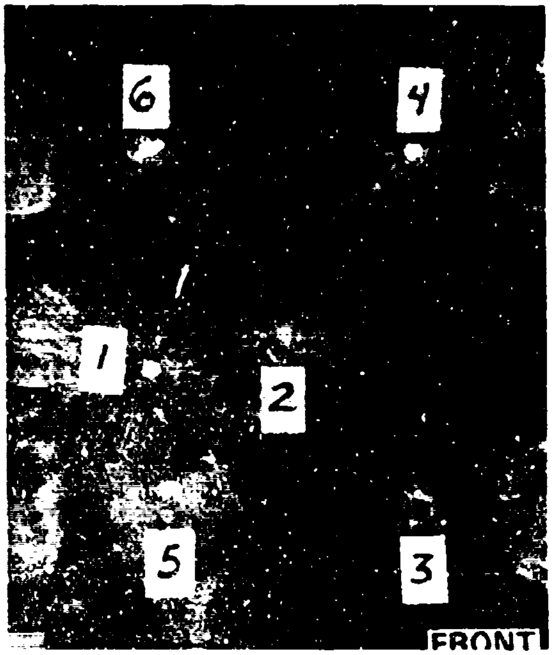


c. 171°C (340°F)

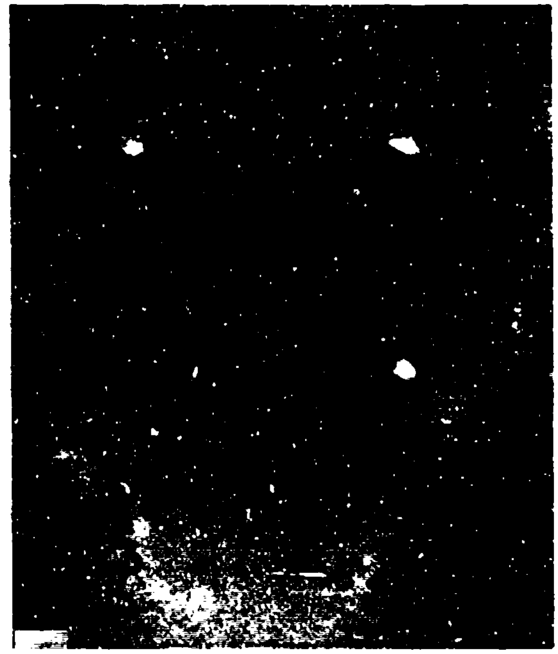


d. 171°C (340°F)

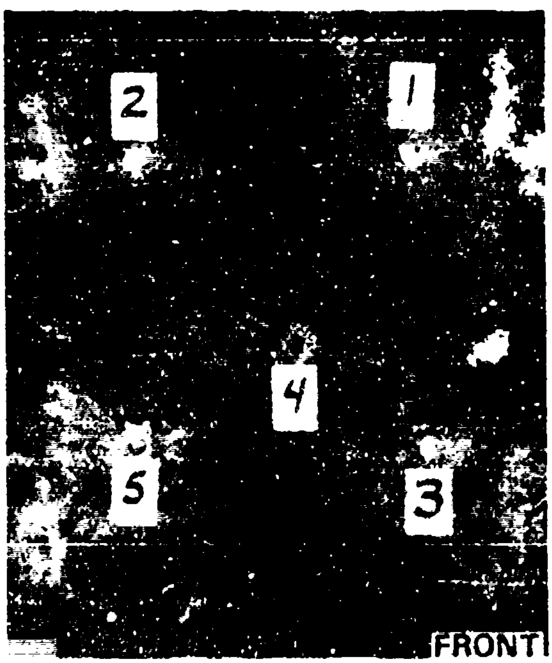
Figure 6. Ballistic tested ESR 4340 steel plates with a 0.635 cm (0.250 inch) nominal thickness as a function of tempering temperature. (75% reduction)



e. 191°C (375°F)



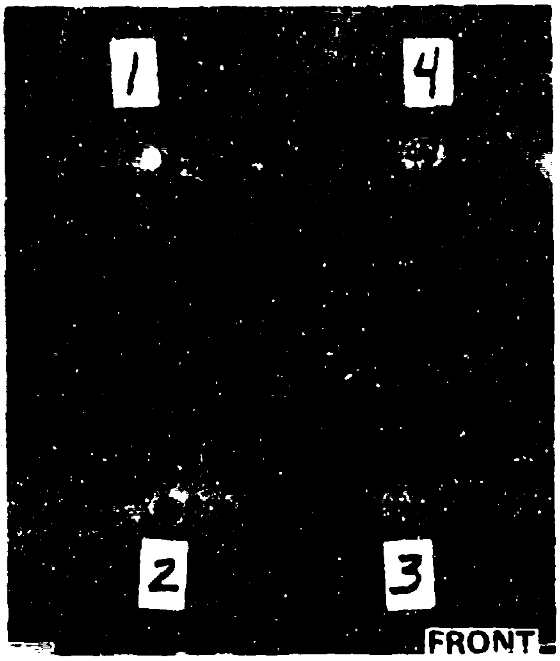
f. 191°C (375°F)



g. 204°C (400°F)

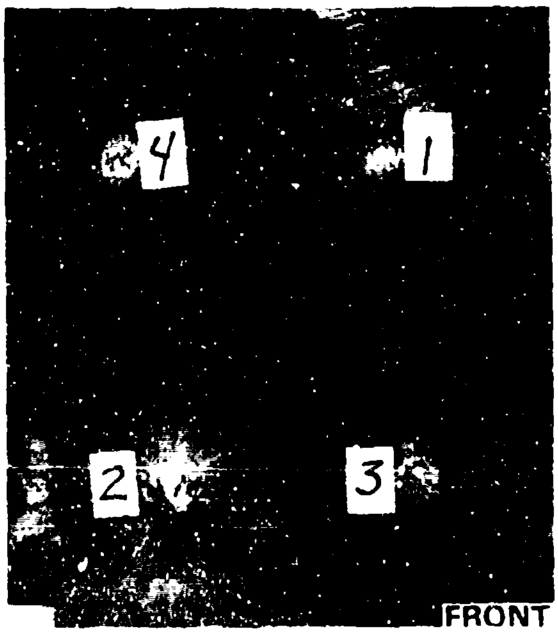
h. 204°C (400°F)

Figure 8. Ballistic tested ESR 4340 steel plates with a 0.635 cm (0.250 inch) nominal thickness as a function of tempering temperature. (75% reduction)



a. 0.820 cm (0.323 inch)

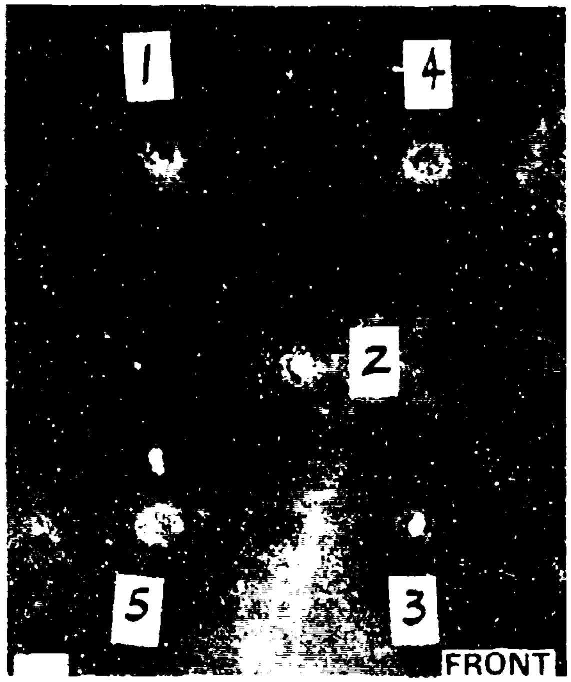
b. 0.820 cm (0.323 inch)



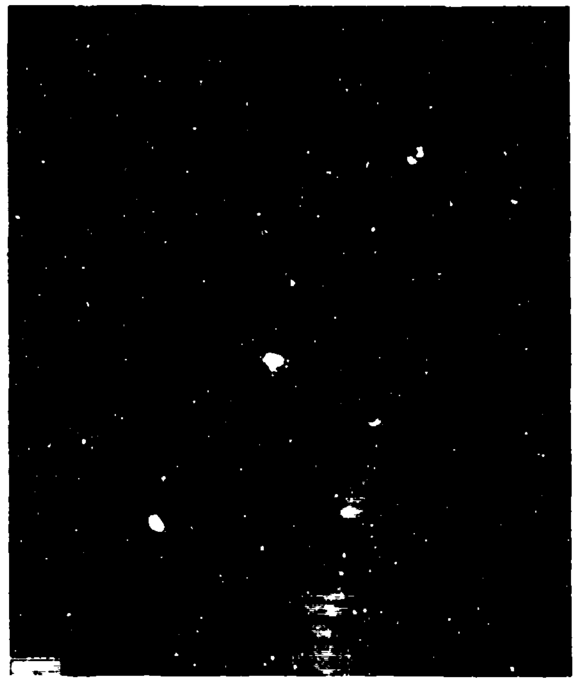
c. 0.886 cm (0.349 inch)

d. 0.886 cm (0.349 inch)

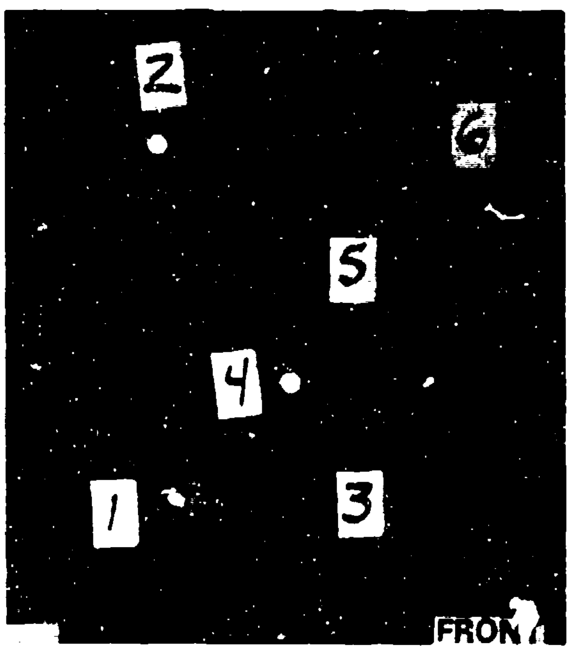
Figure 7. Ballistic tested VAR 4340 steel tempered at 171°C (340°F) for various thicknesses. (75% reduction)



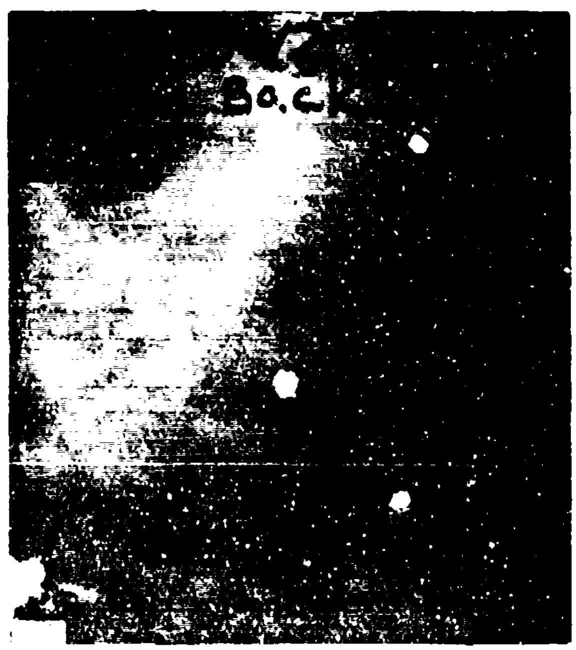
e. 0.930 cm (0.366 inch)



f. 0.930 cm (0.366 inch)

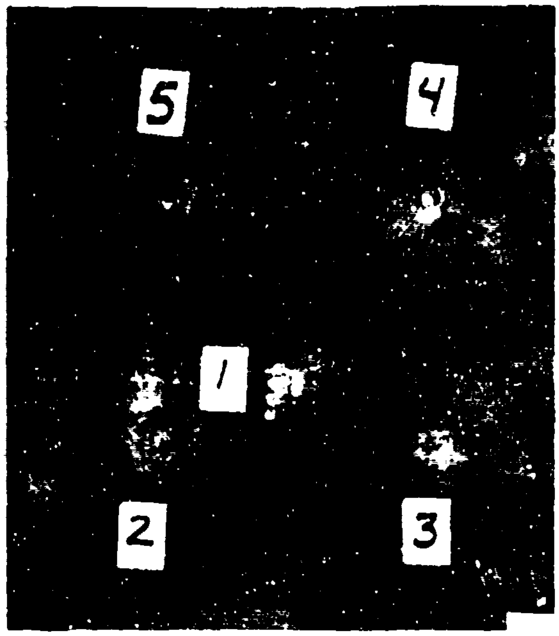


g. 1.20 cm (0.471 inch)

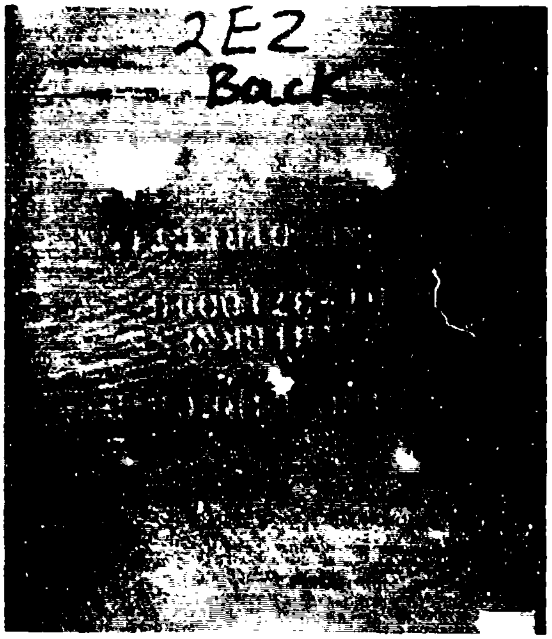


h. 1.20 cm (0.471 inch)

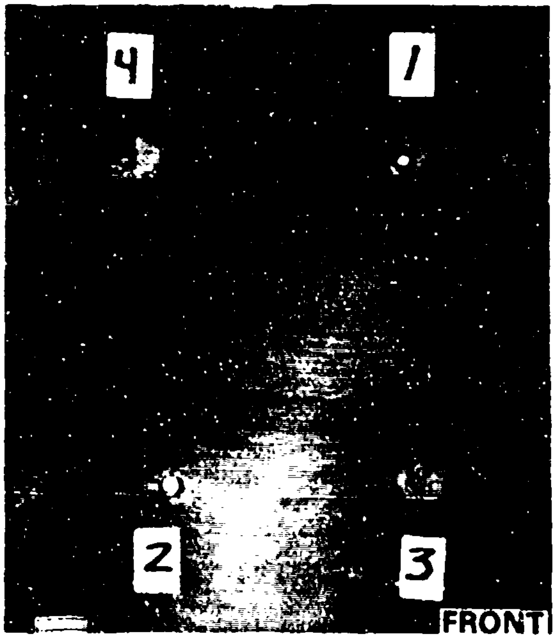
Figure 7. Ballistic tested VAR 4340 steel tempered at 171°C (340°F) for various thicknesses. (75% reduction)



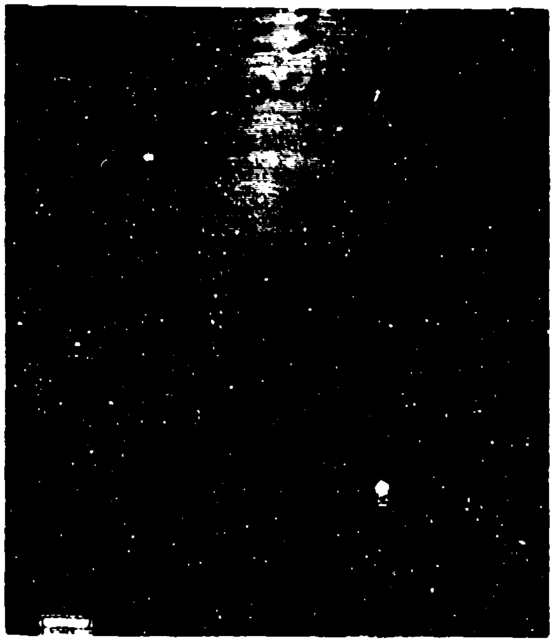
a. 0.820 cm (0.323 inch)



b. 0.820 cm (0.323 inch)

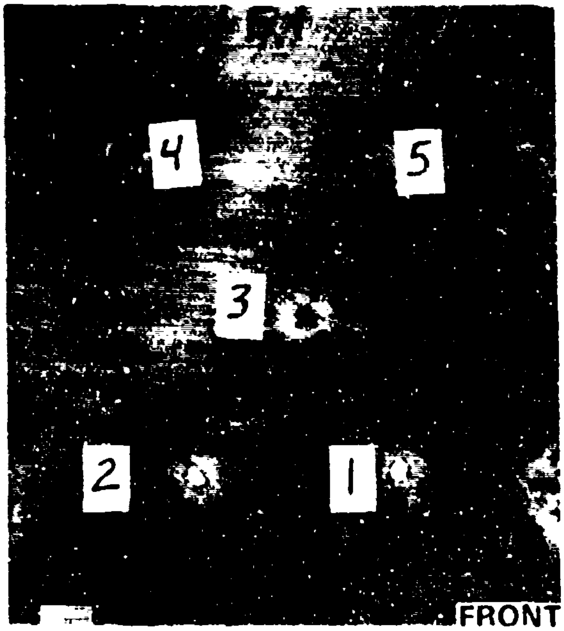


c. 0.914 cm (0.360 inch)



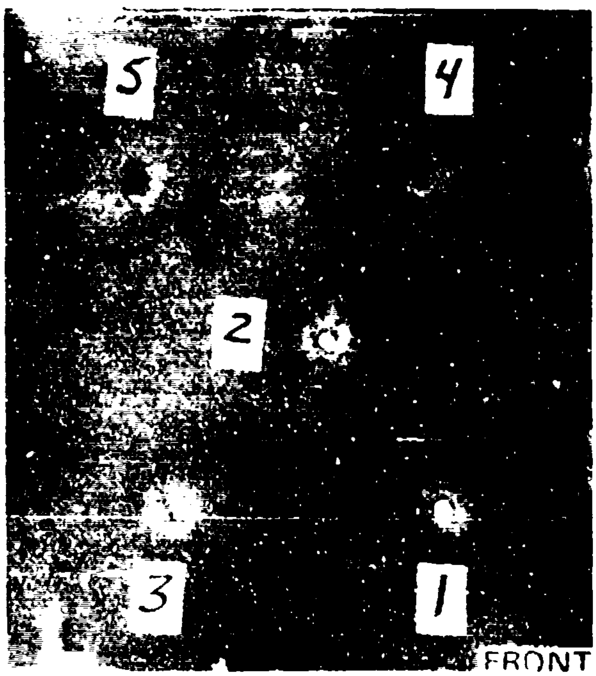
d. 0.914 cm (0.360 inch)

Figure 8. Ballistic tested ESR 4340 steel tempered at 171°C (340°F) for various thicknesses. (75% reduction)

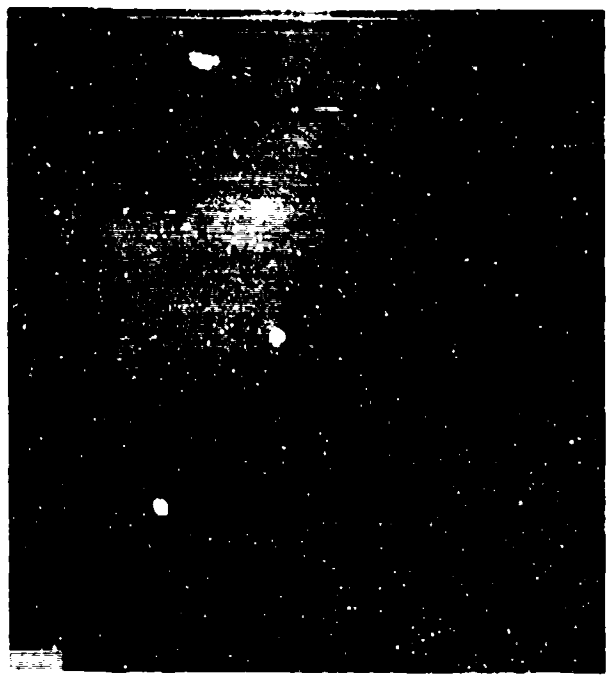


e. 1.01 cm (0.396 inch)

f. 1.01 cm (0.396 inch)

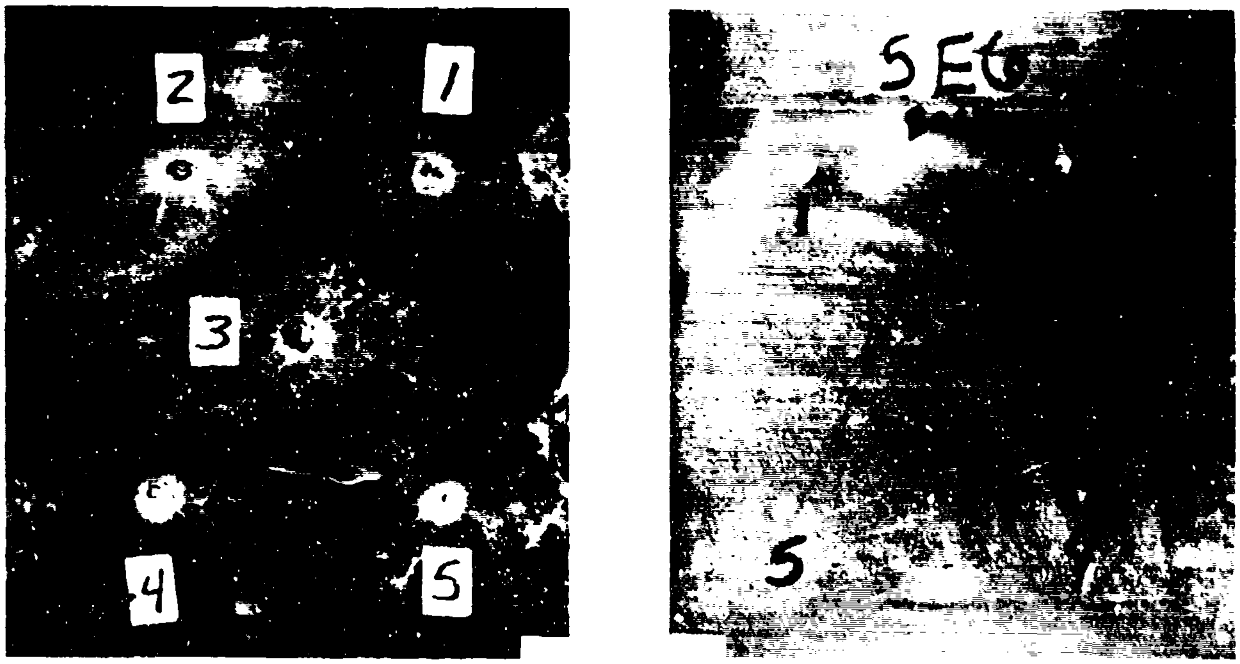


g. 1.15 cm (0.452 inch)



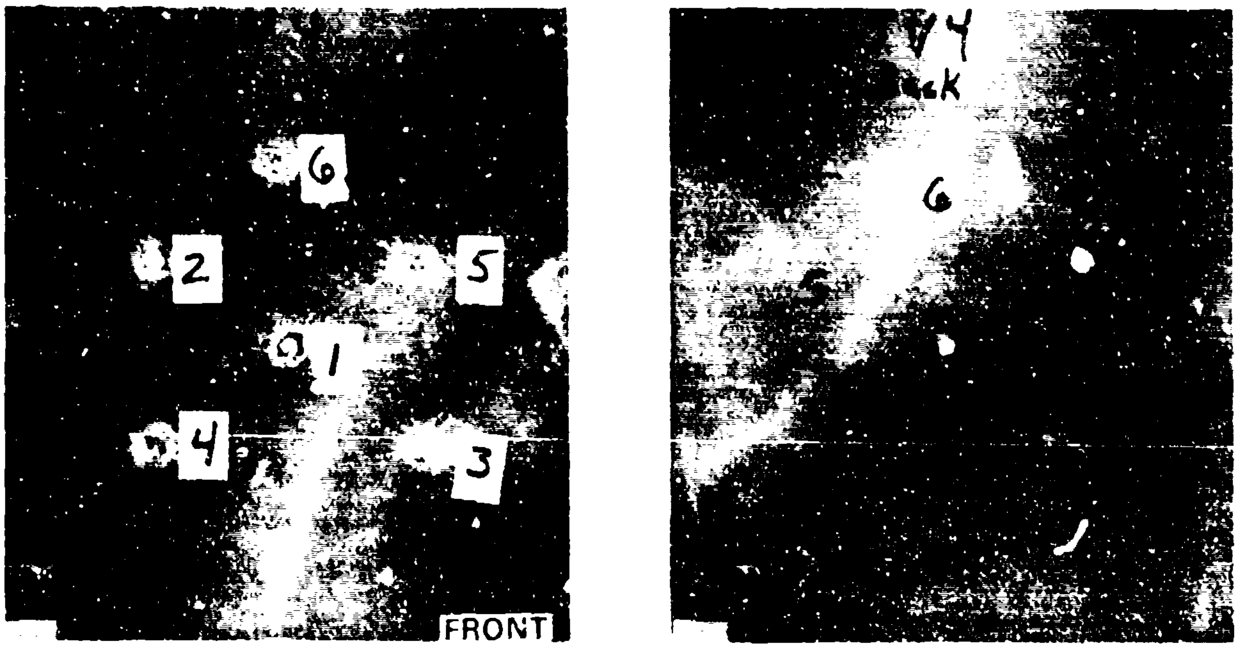
h. 1.15 cm (0.452 inch)

Figure 8. Ballistic tested ESR 4340 steel tempered at 171°C (340°F) for various thicknesses. (75% reduction)



a.   b.

Figure 9. Ballistic tested ESR 4340 steel 1.05-cm (0.413 inch) thick plate tempered at 191°C (375°F). (76% reduction)



a   b.

Figure 10. Ballistic tested VAR 4340 steel 1.18-cm (0.463 inch) thick plate tempered at 191°C (375°F). (75% reduction)

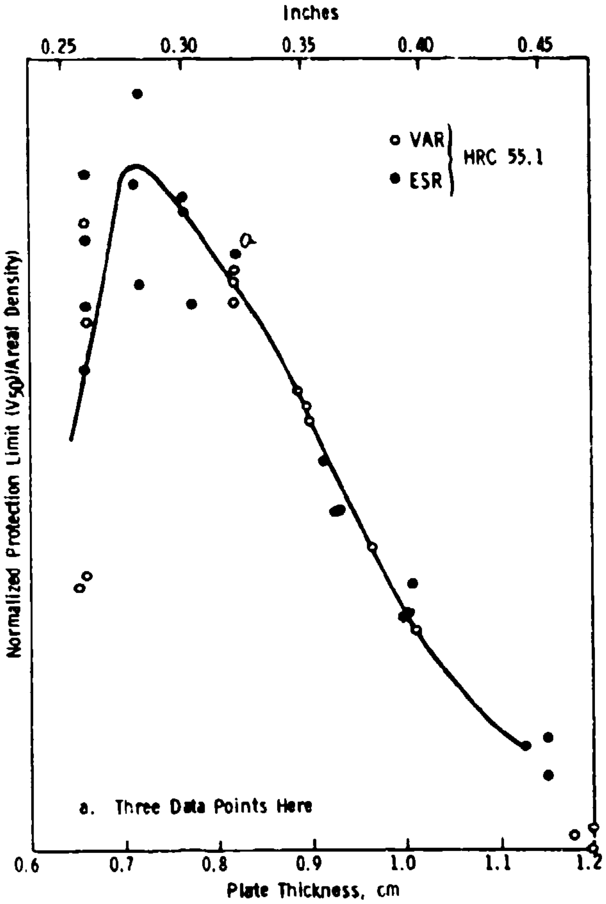
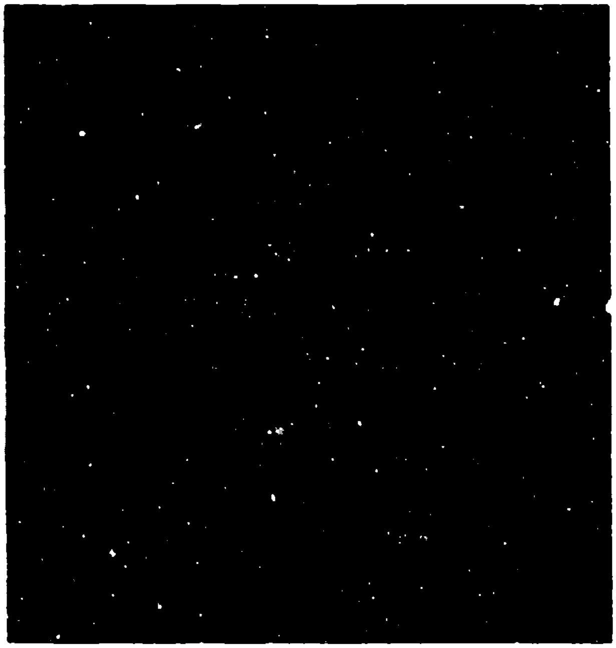


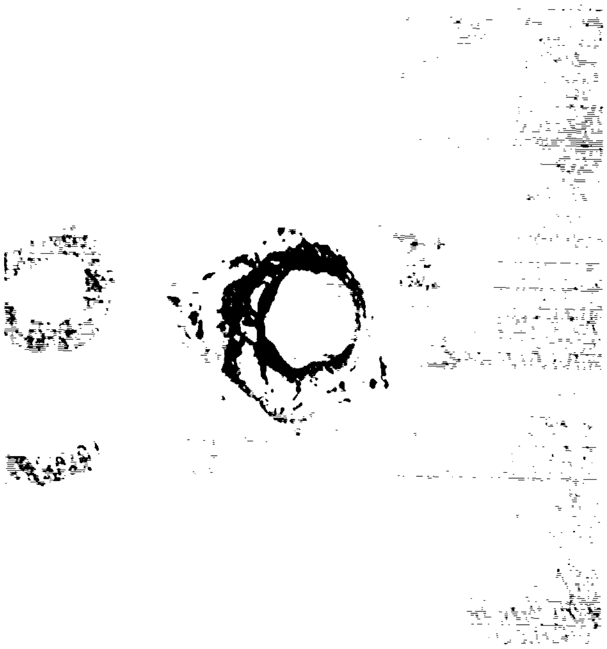
Figure 11. Normalized protection limit as a function of plate thickness for ESR and VAR 4340 steel tempered at 171°C (340°F) ballistically impacted with .50 caliber AP M2 projectiles.



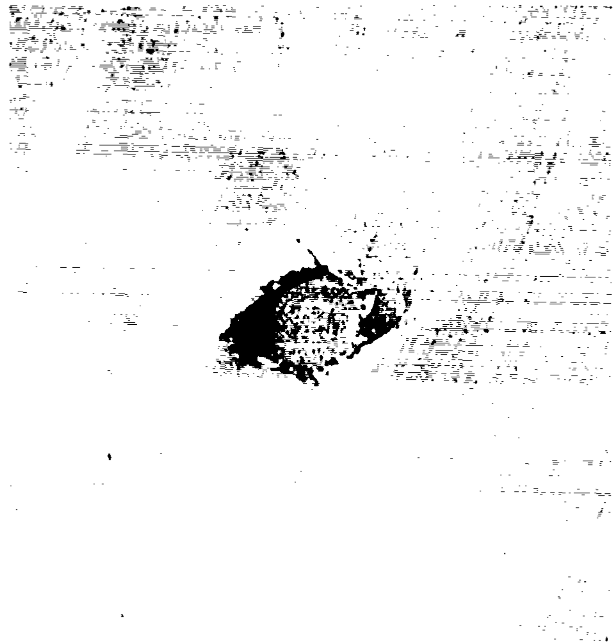
a. 0.64 cm (0.25 inch) - Front

b. 0.64 cm (0.25 inch) - Back

Figure 12. Typical ballistic penetrations for .50 caliber AP M2 threat at velocities ±19 m/s (62 ft/s) from V_{50} against ESR 4340 steel tempered at 171°C (340°F) as a function of thickness. Mag. 2X



c. 0.91 cm (0.36 inch) - Front



d. 0.91 cm (0.36 inch) - Back

e. 1.14 cm (0.45 inch) - Front

f. 1.14 cm (0.45 inch) - Back

Figure 12. Typical ballistic penetrations for .50 caliber AP M2 threat at velocities ±19 m/s (62 ft/s) from V_{50} against ESR 4340 steel tempered at 171°C (340°F) as a function of thickness. Mag. 2X

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COMPARISON OF BALLISTIC PERFORMANCE OF A
SPLIT HEAT OF ESR AND VAR 4340 STEEL -
Charles F. Hickey, Jr., Timothy S. Thomas,
and Albert A. Anctil

Technical Report AMMRC TR 85-20, July 1985, 26 pp -
illus-tables, D/A Project 1L162105AH84,
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Key Words

Low alloy steels
Electroslag remelting
Vacuum arc remelting

A split argon-oxygen decarburized (AOD) heat of 4340 steel was used to compare the relative effectiveness of the VAR and ESR processes on ballistic performance. Forgings of VAR and ESR 4340 steel were rolled into plates with thicknesses of 0.64, 0.81, 0.96, 1.12, and 1.27 cm (0.25, 0.32, 0.38, 0.44, and 0.50 inch). Plates were heat treated to a tempered martensite microstructure by oil quenching and then tempering at 163, 171, 191, or 204°C (325, 340, 375, or 400°F). The protection limit (V_{50}) for a .50 caliber AP M2 threat was determined for ESR and VAR 4340 steel plates of several thickness tempering temperature combinations. Results indicate that over the thickness range studied the protection limit for the ESR 4340 steel tempered at 171°C (340°F) is equal to or greater than that of the VAR 4340 steel. Also, within the tempering temperature range studied the 171°C (340°F) temper provides the greatest protection against the .50 caliber threat for 0.64-cm (0.25 inch) thick ESR 4340 steel plates. There is a greater tendency for VAR processed 0.64-cm (0.25 inch) thick plates tempered at 163 and 171°C (325 and 340°F) to crack when impacted by this threat than comparable ESR processed plates. Further, for both ESR and VAR 4340 steel plates tempered at 171°C (340°F) it is found that the penetration mechanism gradually changes from petalling to plugging as plate thickness increases.

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